Rare earth doped non-oxide glasses for mid-IR fiber lasers

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Outline:

1. Overview of mid-IR rare earth transitions
   - need for non-oxide glass host
2. Nonradiative relaxation
   - theory and experiment
3. Fiber lasers demonstrated to date
4. Fiber laser modeling
   - cascade lasing to avoid bottlenecking
   - include fiber attenuation loss

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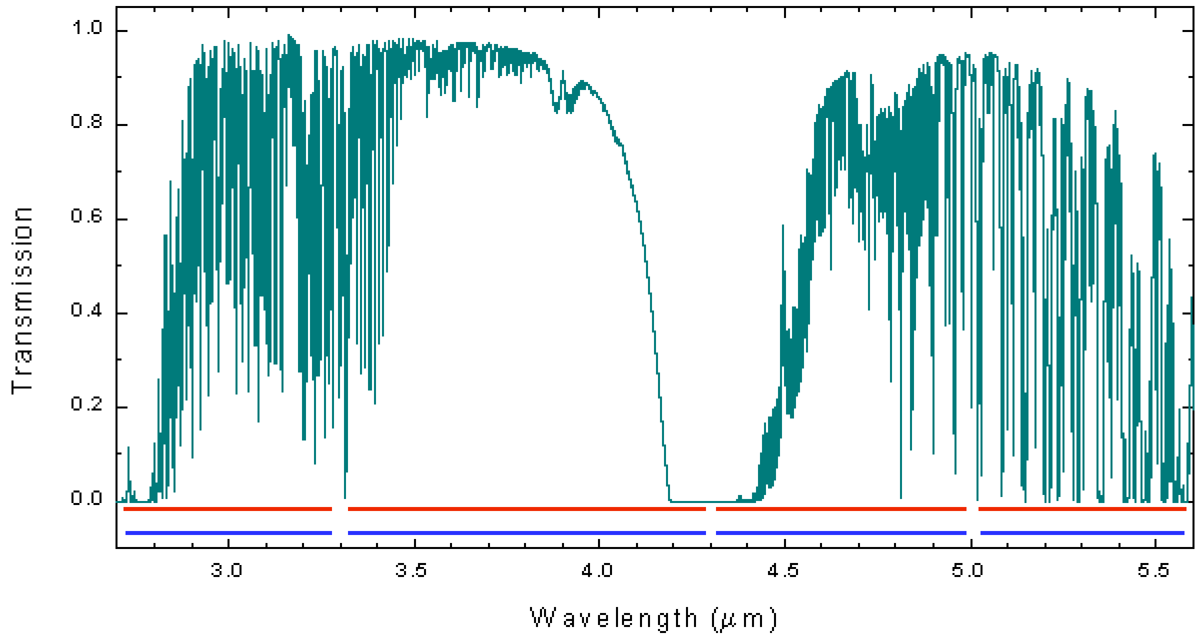
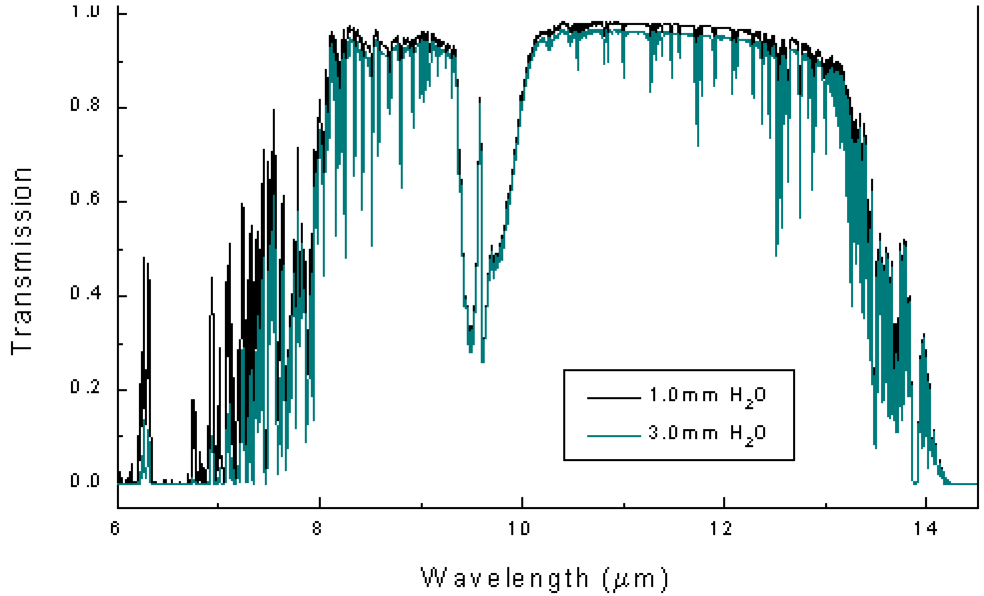


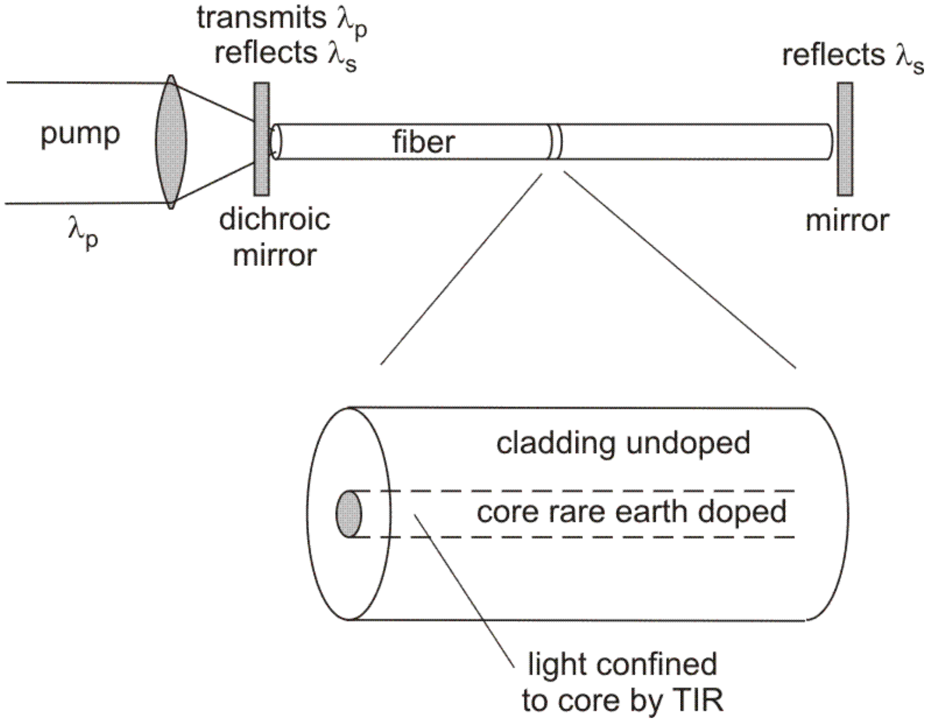
Atmospheric transmission spectra above Mauna Kea

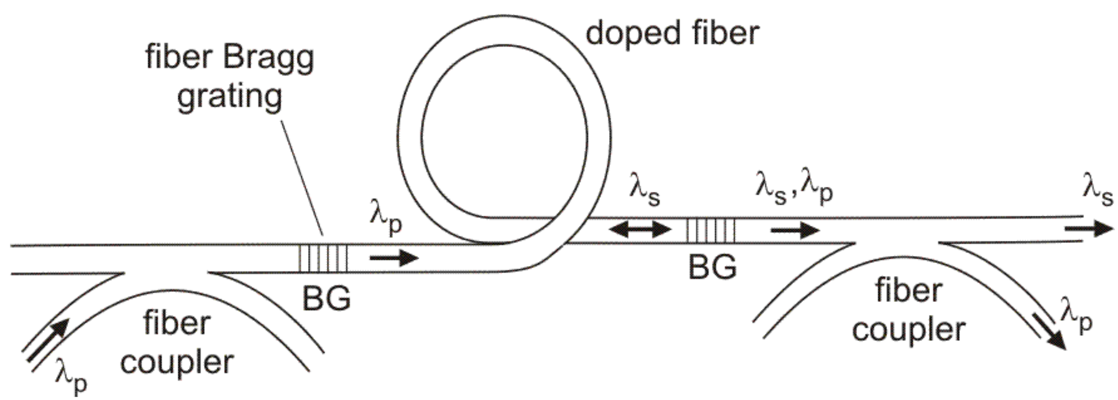


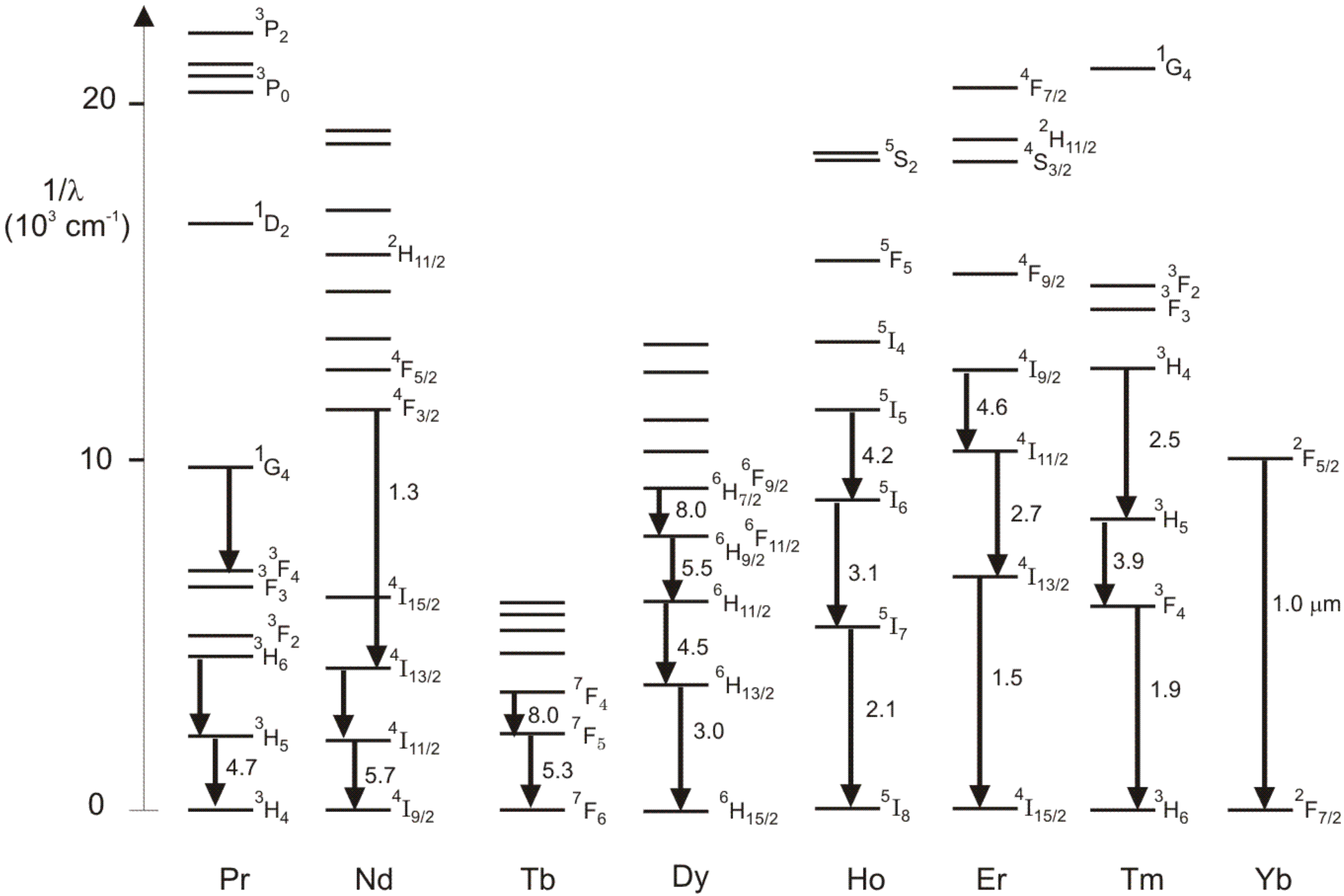
Note: For IRCM avoid 4.2-4.5 μm and 9.4-10 μm

http://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints/ir-transmission-spectra

Fiber laser schemes





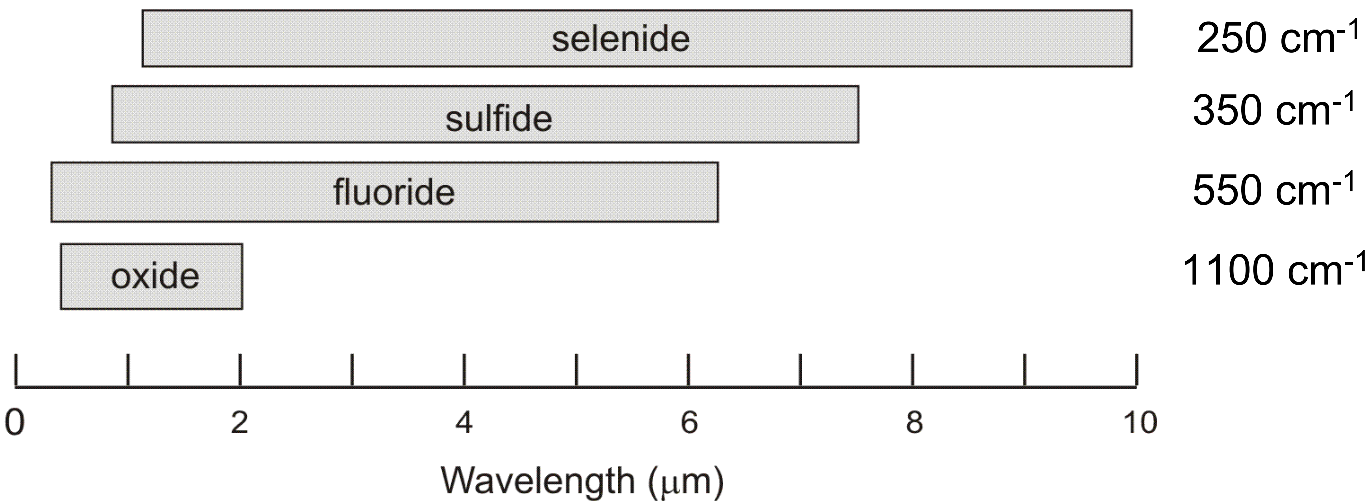


$1/\lambda$
$(10^3\ cm^{-1})$
20
10
0
$^3P_2$
$^3P_0$
$^1D_2$
$^1G_4$
$^3F_4$
$^3F_3$
$^3F_2$
$^3H_6$
$^3H_5$
4.7
$^3H_4$
$^2H_{11/2}$
$^4F_{5/2}$
$^4F_{3/2}$
1.3
$^4I_{15/2}$
$^4I_{13/2}$
$^4I_{11/2}$
5.7
$^4I_{9/2}$
$^7F_4$
8.0
$^7F_5$
5.3
$^7F_6$
$^6H_{7/2}$ $^6F_{9/2}$
8.0
$^6H_{9/2}$ $^6F_{11/2}$
5.5
$^6H_{11/2}$
4.5
$^6H_{13/2}$
3.0
$^6H_{15/2}$
$^5S_2$
$^5F_5$
$^5I_4$
$^5I_5$
4.2
$^5I_6$
3.1
$^5I_7$
2.1
$^5I_8$
$^4F_{7/2}$
$^2H_{11/2}$
$^4S_{3/2}$
$^4F_{9/2}$
$^4I_{9/2}$
4.6
$^4I_{11/2}$
2.7
$^4I_{13/2}$
1.5
$^4I_{15/2}$
$^1G_4$
$^3F_2$
$^3F_3$
$^3H_4$
2.5
$^3H_5$
3.9
$^3F_4$
1.9
$^3H_6$
$^2F_{5/2}$
1.0 μm
$^2F_{7/2}$
Pr
Nd
Tb
Dy
Ho
Er
Tm
Yb

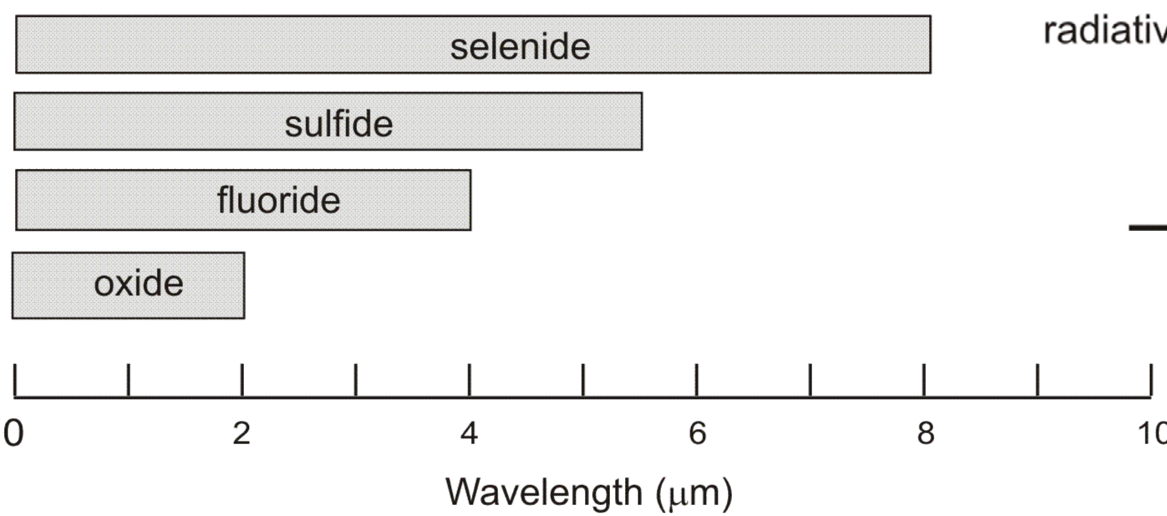
Upper limit on transition wavelength set by:

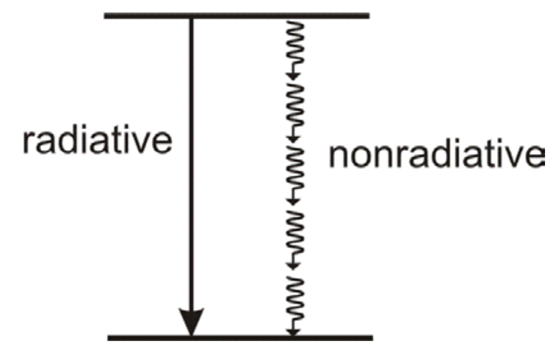
- Optical transparency band of glass host

$\hbar\omega_v$



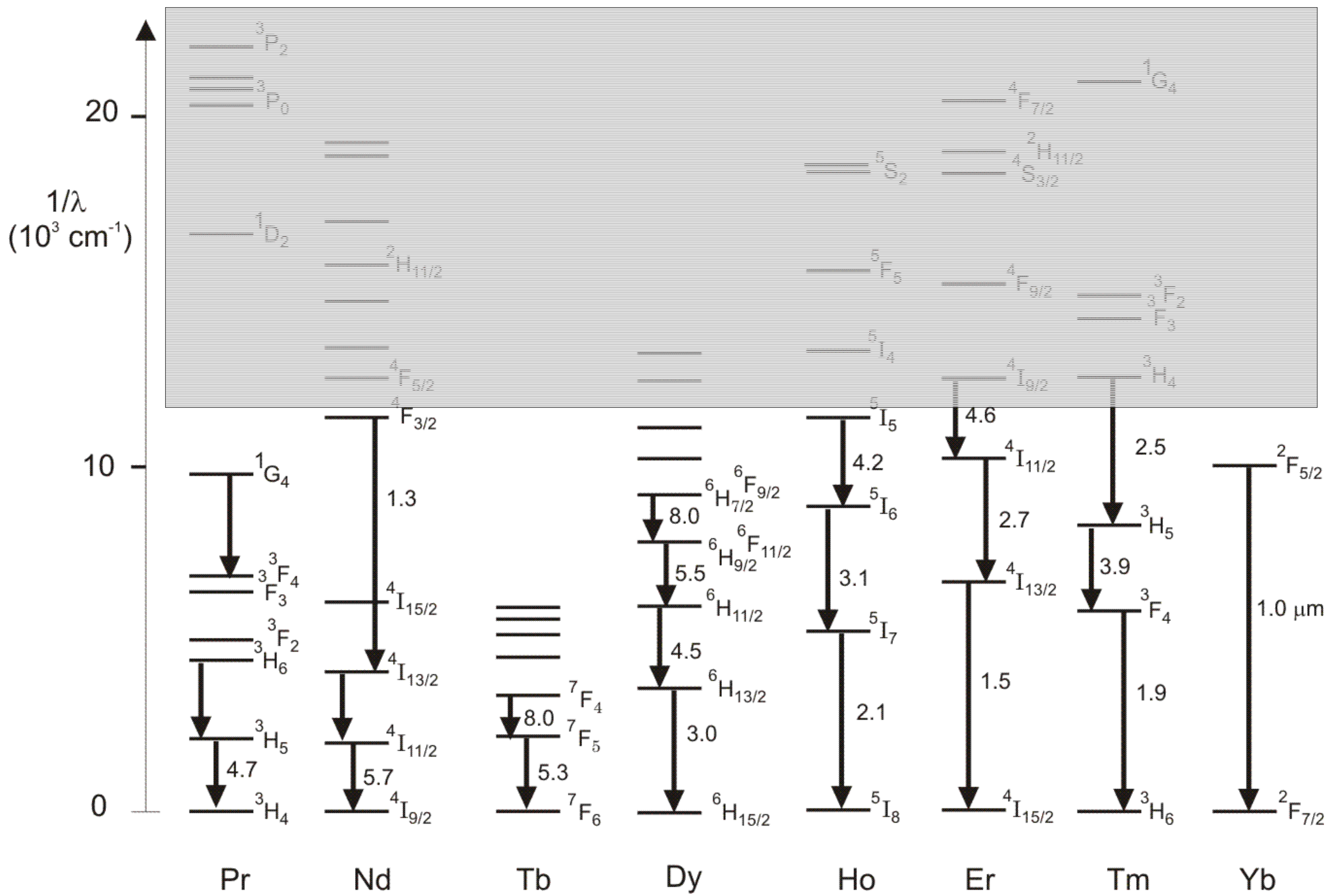
- Nonradiative quenching of upper laser level



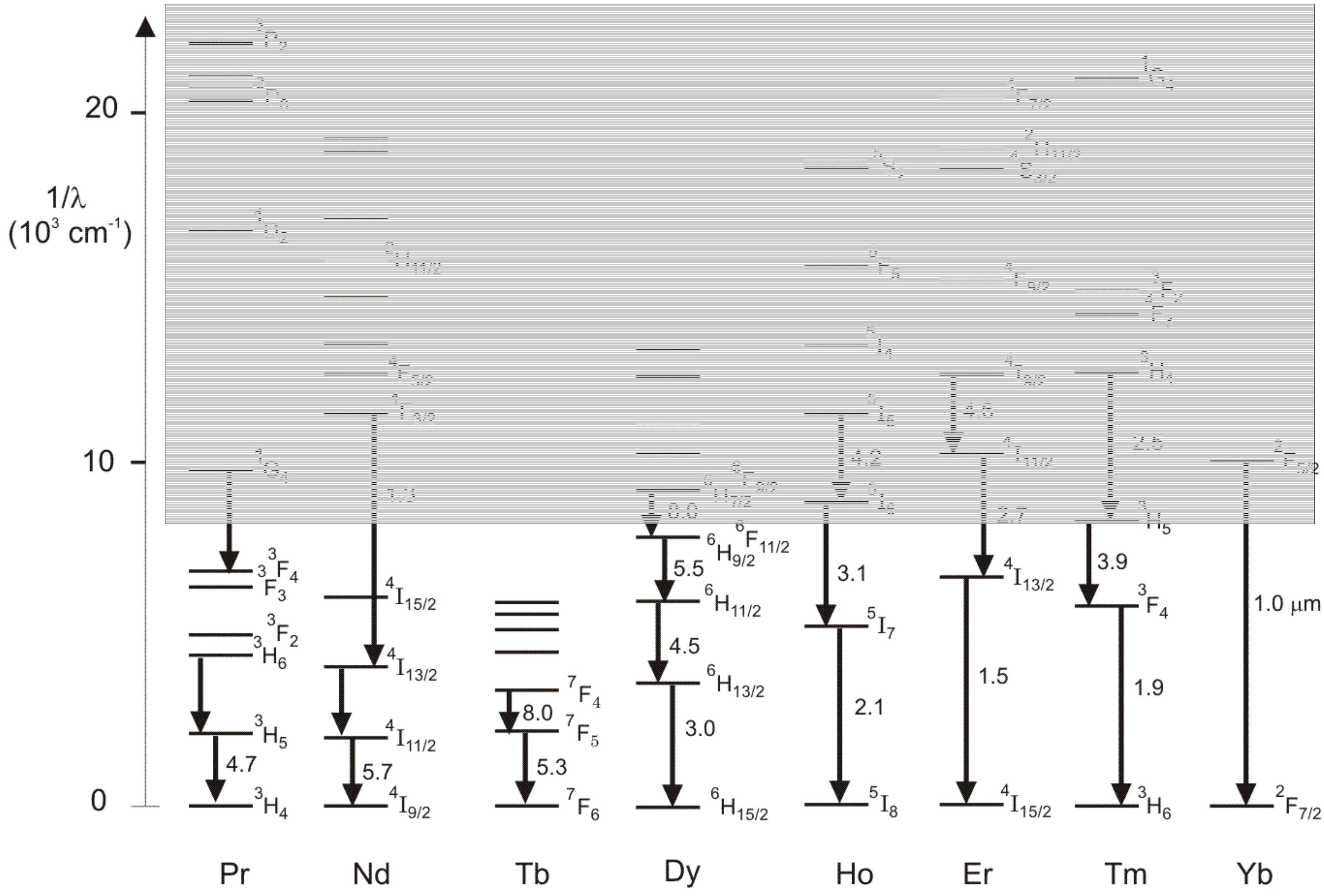


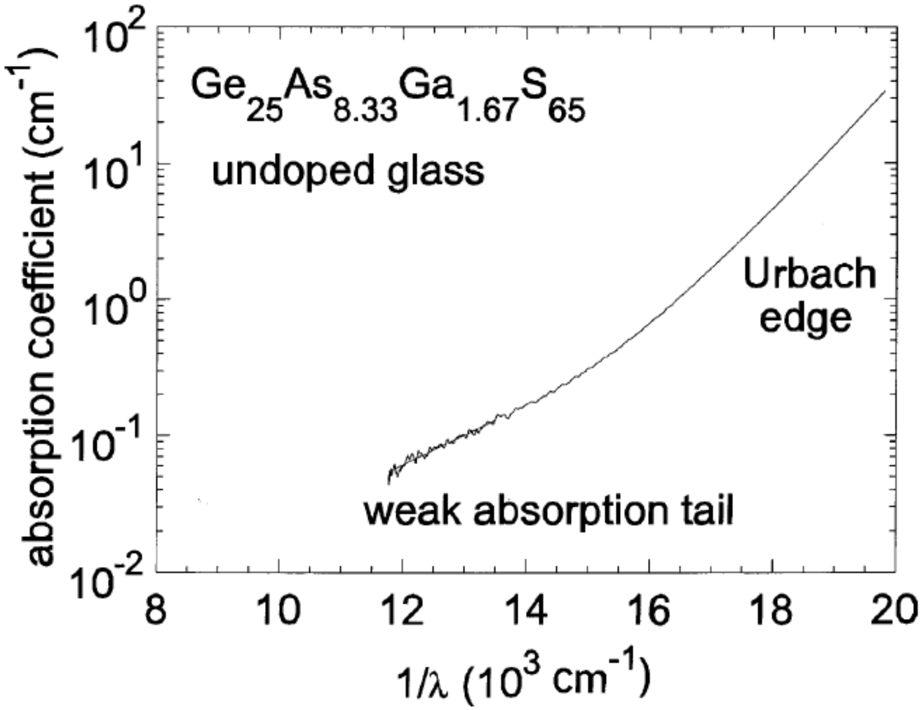
Rule of thumb:
Need more than
5 phonons to
bridge gap

Sulfide glass host



Selenide glass host

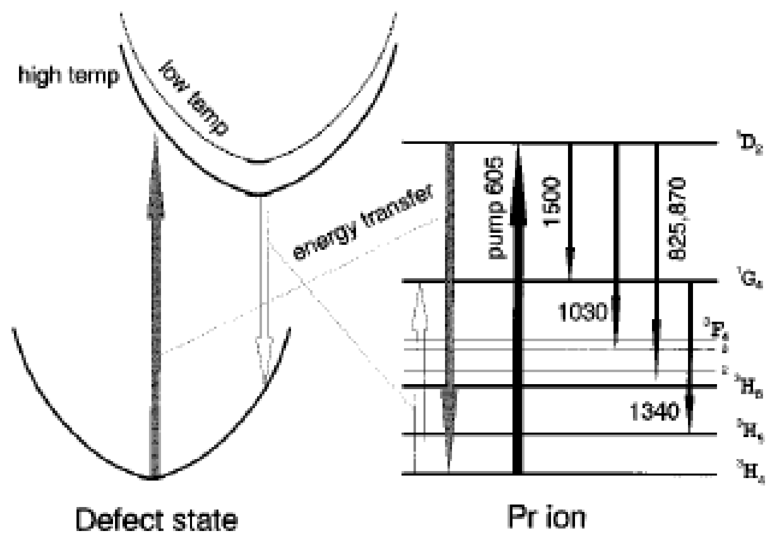




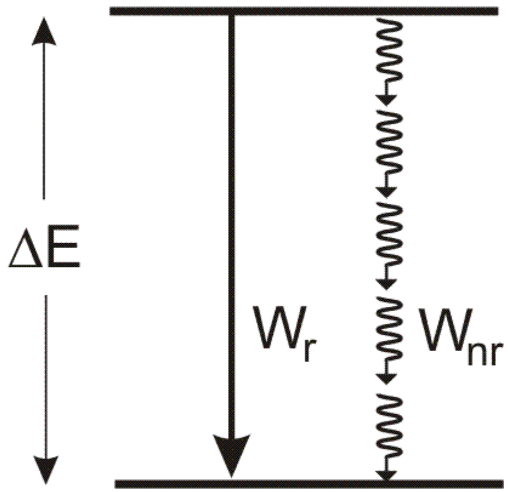
- Definition of band gap is somewhat arbitrary
- Can take $\alpha \sim 1$ cm^{-1} as measure of band edge
- Still absorption well below band edge due to defect states

- Energy can be transferred between rare earth and glass defect state

Quimby and Aitken, J. Appl. Phys. **82**, 3992 (1997)



Nonradiative relaxation:
does the energy gap law work in chalcogenide glasses?



$$W_{mp}(T) = B[1 + n(T)]^p e^{-\alpha \Delta E}$$

multiphonon relaxation rate

$$n(T) = [e^{\hbar\omega/kT} - 1]^{-1}$$

thermally generated phonons per mode

$$p = \Delta E/\hbar\omega$$

number of phonons needed to bridge gap

At finite temperature T:

$$W_{mp}(T) = Be^{-\alpha' \Delta E}$$

where

$$\alpha' \equiv \alpha - \frac{\ln(1+n)}{\hbar\omega}$$

reduced logarithmic slope at finite T

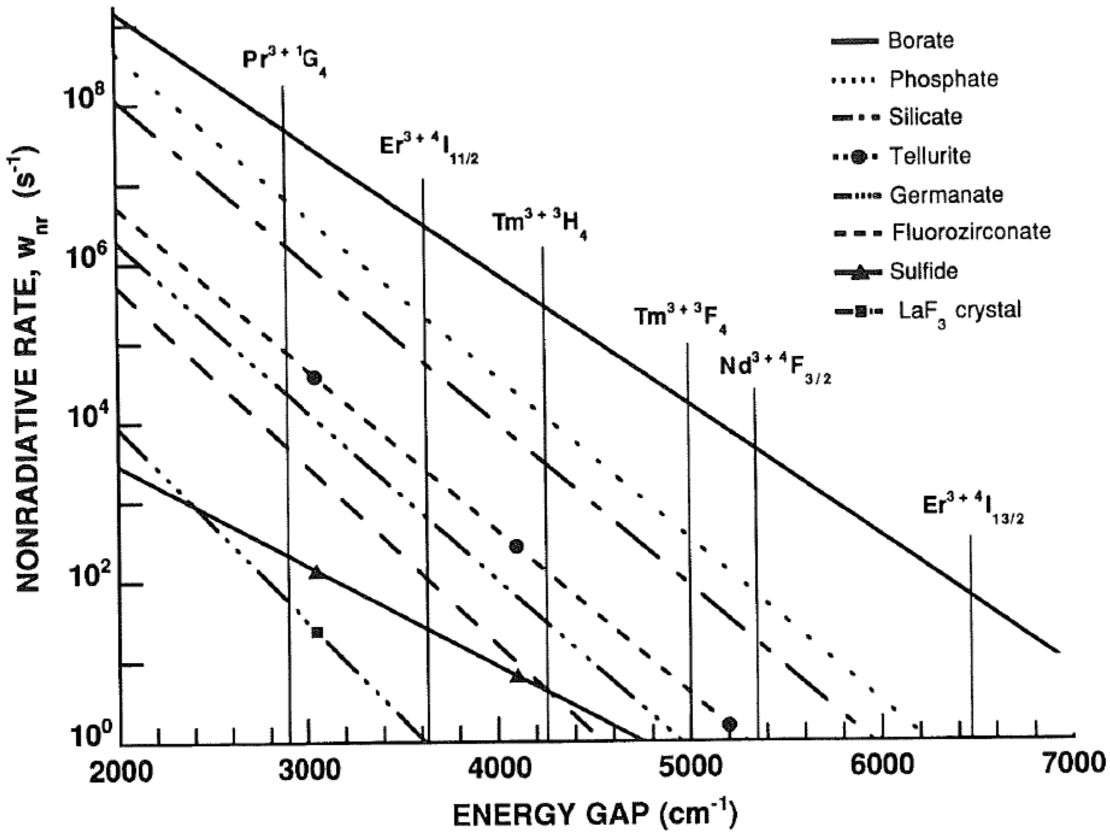
Verifying the energy gap law experimentally

Determine nonradiative rate from:

- Calculated radiative rate
  - Judd-Ofelt analysis <u>or</u>
  - reciprocity relation
- Measured total rate
  - fluorescence lifetime

$$1/\tau = W_r + W_{nr}$$

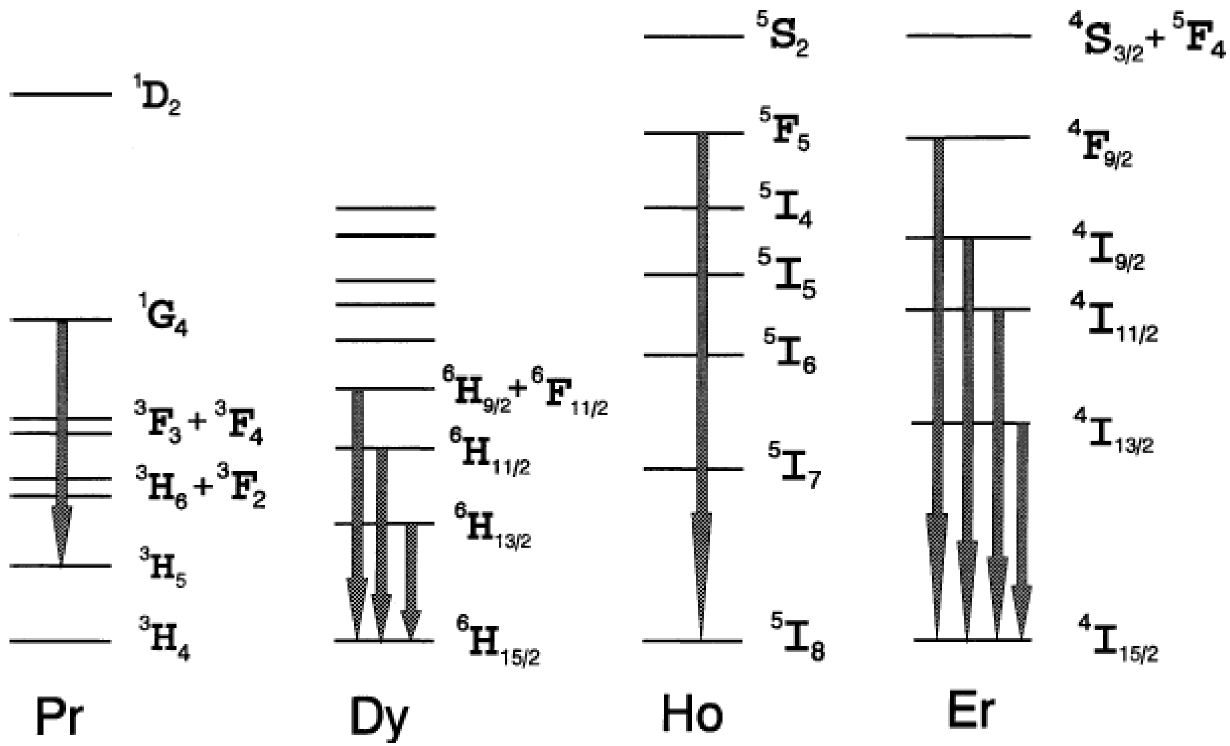
- sulfide glass appears anomalous in this plot (parameters from Reisfeld)
- question: are the nonradiative rates at large energy gap influenced by additional nonradiative processes?



from Miniscalco, in *Rare Earth Doped Fiber Lasers and Amplifiers*, ed. M.J.F. Digonnet (Marcel Dekker 1993)

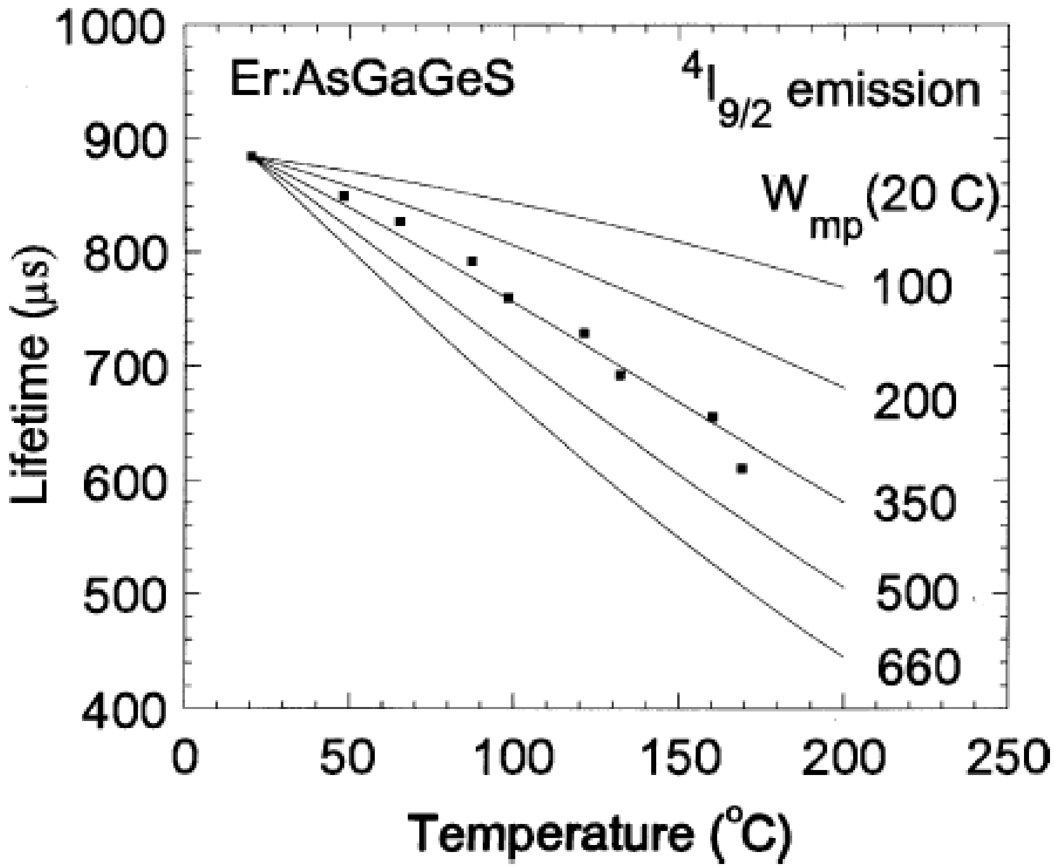
$$\frac{1}{\tau} = W_r + W_{mp} + W_{other}$$

Experimental determination of energy gap law parameters



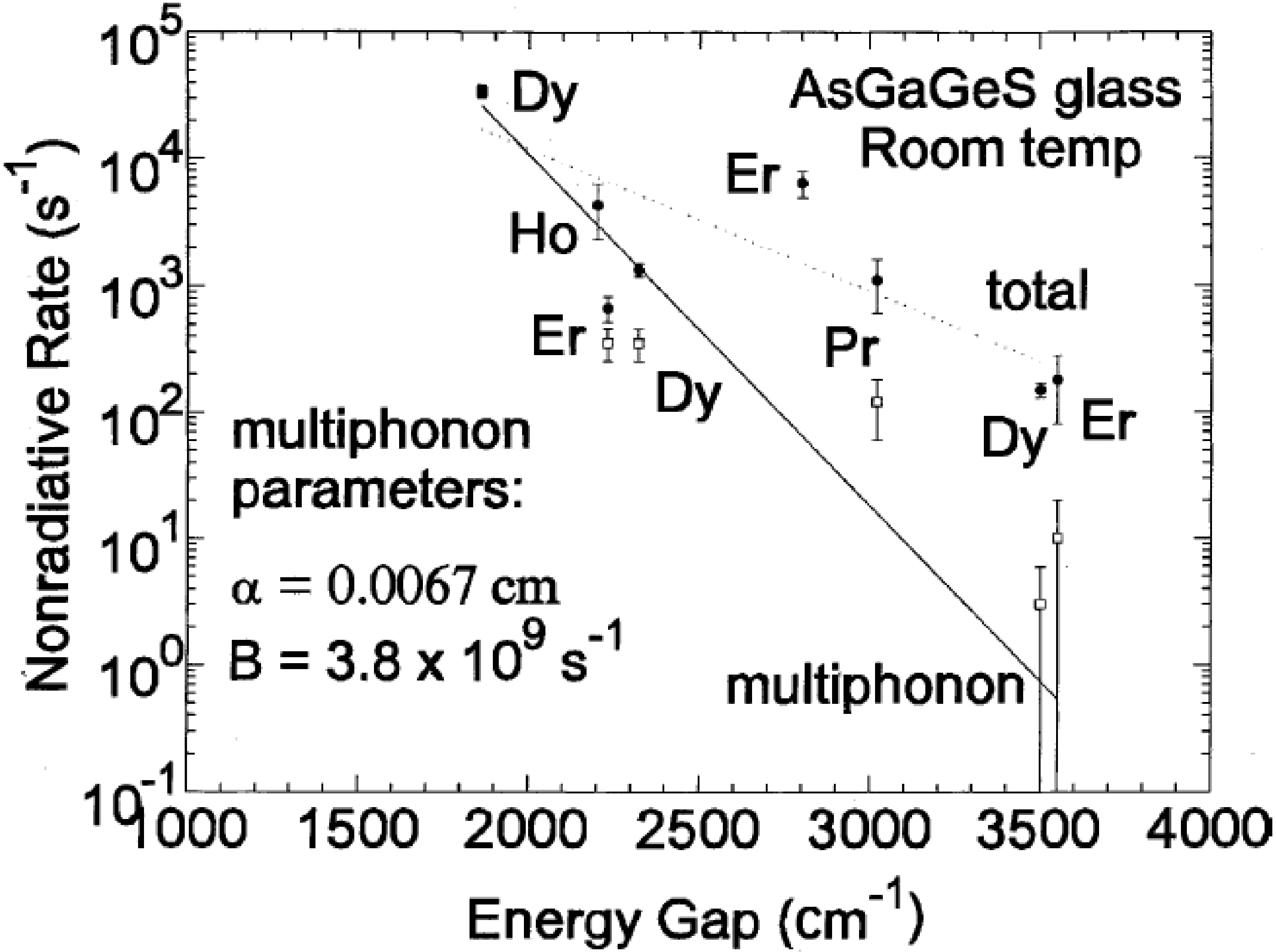
1. Measure absorption spectra, do Judd-Ofelt analysis
2. Calculate all radiative decay rates
3. Measure fluorescence lifetimes for above transitions
4. Determine total nonradiative rate from $W_{nr} = 1/\tau - W_r$
5. Vary temperature to determine the true multiphonon rate

Example variation of fluorescence lifetime with temperature



$$W_{\rm mp}(T) = W_{\rm mp}(20^{\circ})\left[\frac{1+n(T)}{1+n(20^{\circ})}\right]^{\rm p}$$

treat $W_{mp}(20^o)$ as adjustable parameter to fit to the data



● total nonradiative decay rate

□ multiphonon decay rate

Origin of extra nonradiative decay

1. Is this real or experimental artifact?
   - Error bars are conservative, and difference is outside error bars
   - For ground state transitions use reciprocity as well as Judd-Ofelt
   - For Pr $^1G_4$ use additional independent method to measure QE
2. Possibly energy transfer to native defects in the glass
   - Mid-gap defect states responsible for photoluminescence, photodarkening, etc.
   - But some transitions (Er $^4I_{13/2}$ – $^4I_{15/2}$) do not suffer additional nonradiative decay
3. More likely: energy transfer to localized vibrational modes
   - H-S vibrations at 2500 and 3200 cm^{-1}
   - Resonance with several Pr, Dy, Er transitions
   - Er $^4I_{9/2}$ lifetime decreases when H-S concentration > 100 ppm [Moizan, SPIE **6469**, 64690E (2007)]
   - Two classes of doped ions:
     - Ions close enough to H-S to be highly quenched
     - Ions far enough away to be unquenched

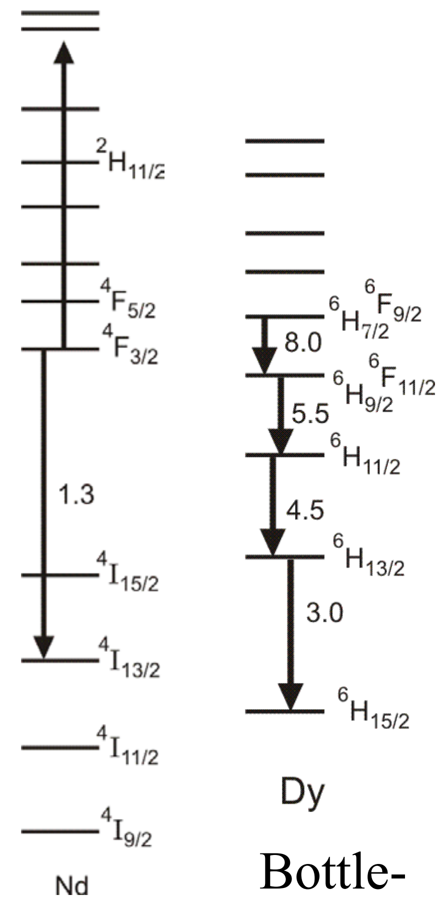
Limits on RE-doped chalcogenide fiber laser performance

1. Nonradiative quenching of upper laser level
   - Need to minimize H-S, H-Se, OH content of glass

2. Excited-state absorption may reduce or eliminate gain
   - Gain may still be possible at certain wavelengths

3. Bottle-necking may limit population inversion
   - Co-dope with 2nd RE ions; energy transfer from lower laser level to added RE ion
   - Maintain population inversion by cascade lasing

4. Fiber attenuation may limit round-trip gain
   - Minimize H-S, H-Se, OH content



ESA

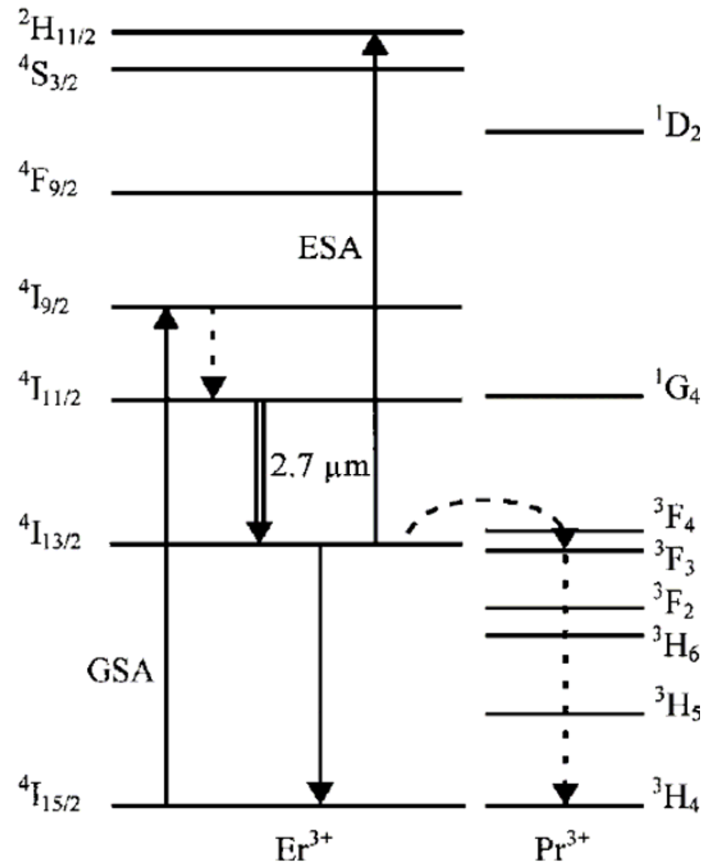
Bottle-necking

Fiber lasers demonstrated to date

Er:ZBLAN $\lambda = 2.75\ \mu m$

Jackson, SPIE **6453**, 64530B (2007)

- Co-doped with Pr to reduce bottle-necking in $^4I_{13/2}$ level
- Double-clad fiber
- Diode pump at 975 nm
- P_{out} ~1.7 W for P_{pump} ~10 W



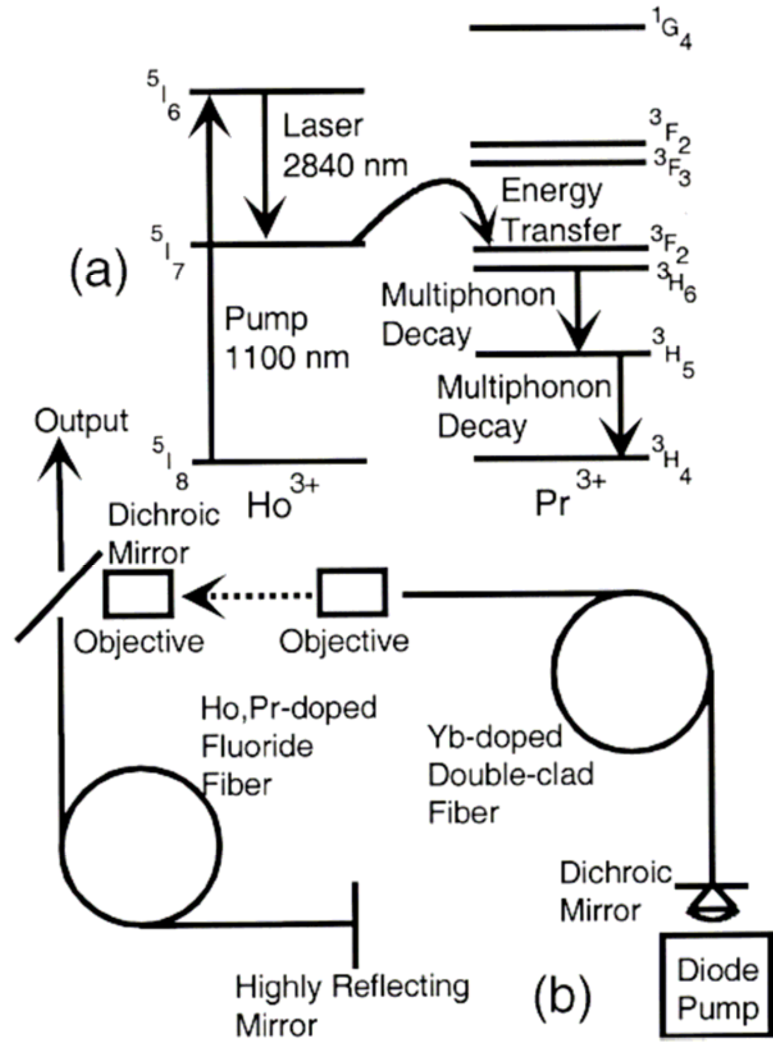
from Jackson et al., Opt. Lett. **24**, 1133 (1999)

Fiber lasers demonstrated to date

Ho:ZBLAN $\lambda = 2.86\ \mu m$

Jackson, SPIE **6453**, 64530B (2007)

- co-doped with Pr to reduce bottle-necking in $^5I_7$ level
- single-mode fiber
- Yb fiber laser pump at 1100 nm
- P_{out} ~2.5 W for P_{pump} ~9 W
- potentially most efficient 3 μm source



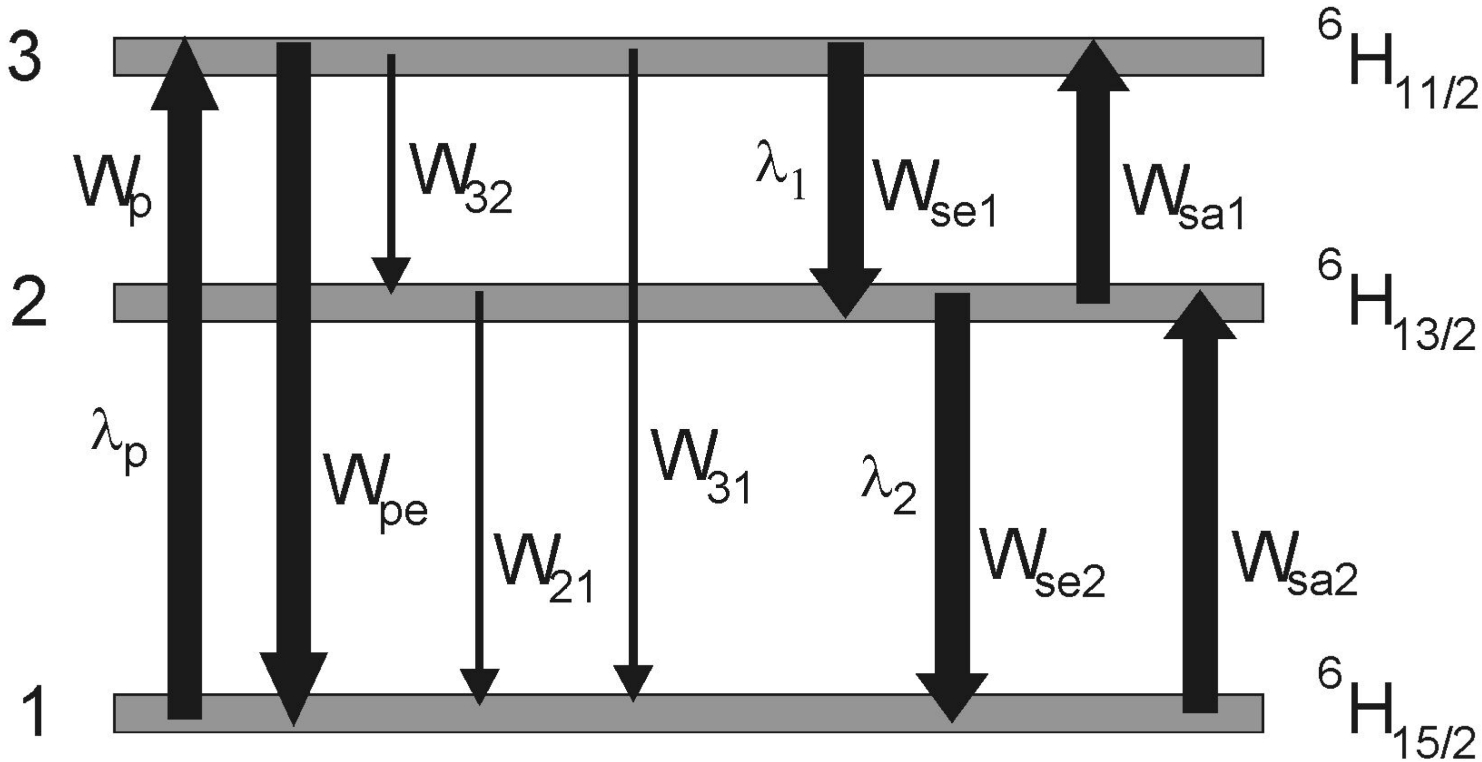
from Jackson et al., Opt. Lett. **29**, 334 (2004)

Fiber lasers demonstrated to date

Beyond 3 μm: ....still waiting....

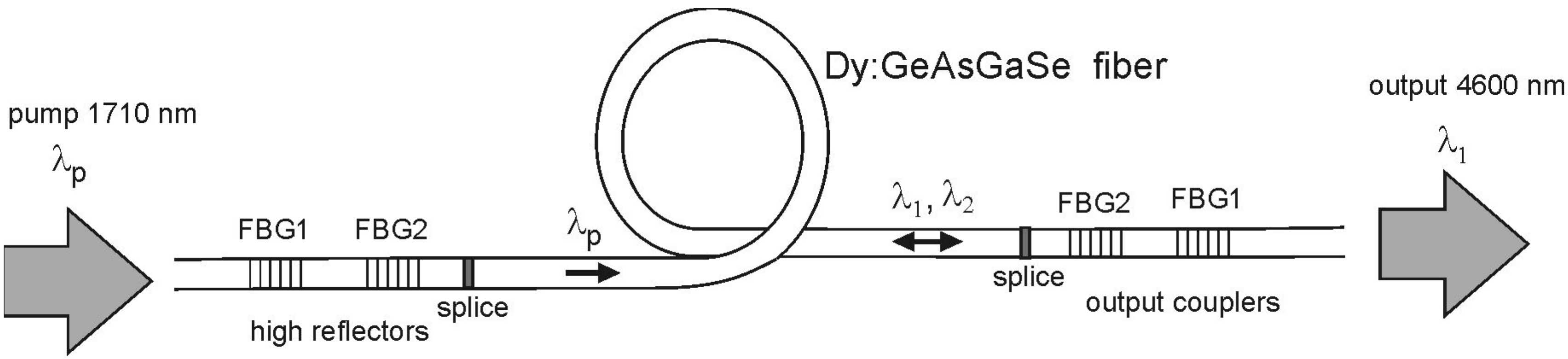
- Wavelength range 4.5 - 4.7 μm of interest
- $^6H_{11/2} \rightarrow {}^6H_{13/2}$ transition of Dy^{3+} possible candidate
- Need low-phonon energy host (chloride crystal, chalcogenide glass)
- Problem: bottlenecking of population due to long lifetime of lower laser level ($^6H_{13/2}$)
- Solution (this work): cascade lasing on the $^6H_{11/2} \rightarrow {}^6H_{13/2}$ and $^6H_{13/2} \rightarrow {}^6H_{15/2}$ transitions can serve to effectively depopulate the $^6H_{13/2}$ level

Dy^{3+} lower energy levels



- model includes stimulated emission and absorption between all three levels
- accounts for an arbitrary degree of population saturation

All-fiber scheme for cascade lasing



Fiber Bragg gratings:

FBG1: lasing wavelength λ_1 = 4600 nm
FBG2: idler wavelength λ_2 = 3350 nm

Model Calculations

$$\frac{dN_3}{dt} = N_1 W_{\mathrm{p}} + N_2 W_{\mathrm{sa1}} - N_3\left(W_{\mathrm{pe}} + W_{\mathrm{se1}} + W_3\right)$$

$$\frac{dN_2}{dt} = N_1 W_{\mathrm{sa2}} - N_2\left(W_{\mathrm{se2}} + W_{\mathrm{sa1}} + W_{21}\right) + N_3\left(W_{\mathrm{se1}} + W_{32}\right)$$

$$N = N_1 + N_2 + N_3$$

Solve rate equations in steady state for level populations N_1, N_2, N_3

$$\gamma_1(z) = \int_0^a \left[N_3(r,z)\sigma_{32} - N_2(r,z)\sigma_{23}\right]\psi_1(r)\, 2\pi r\, dr$$

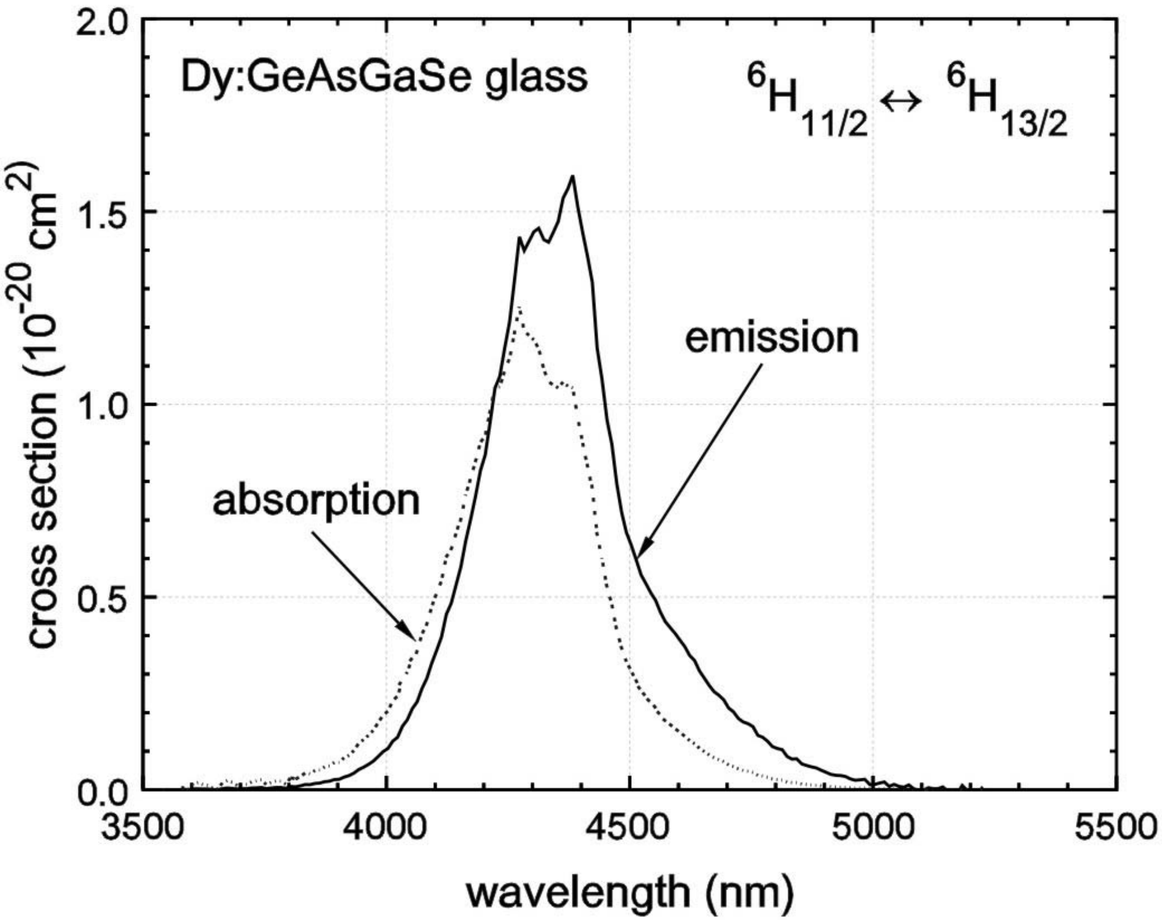
calculate gain/loss coefficients using level populations N_i and light field distribution $\psi(r)$

$$\Delta P_{1+}(z) = \gamma_1(z)\, P_{1+}(z)\, \Delta z$$

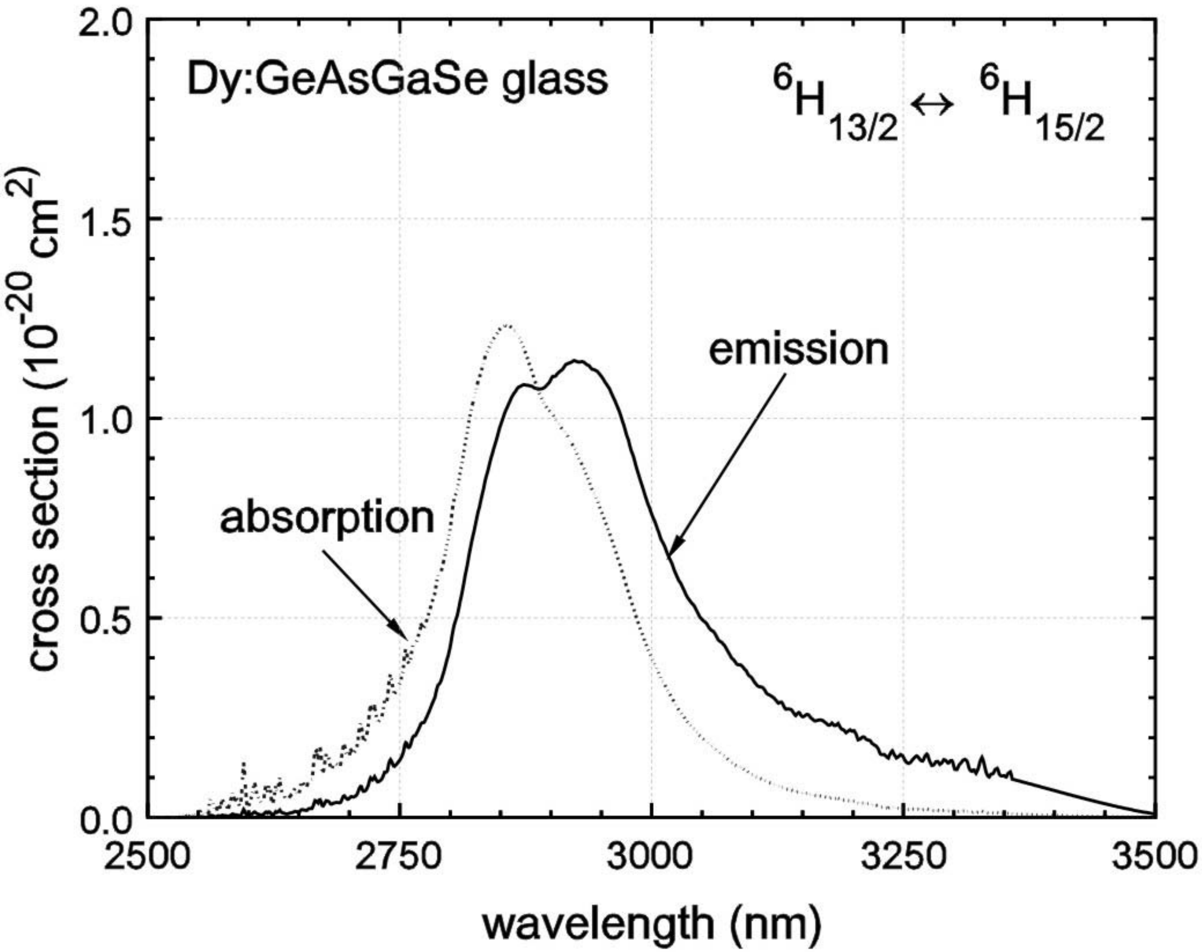
Propagate signal and pump powers back and forth between mirrors until self-consistent solution is obtained

PARAMETERS FOR FIBER LASER MODEL

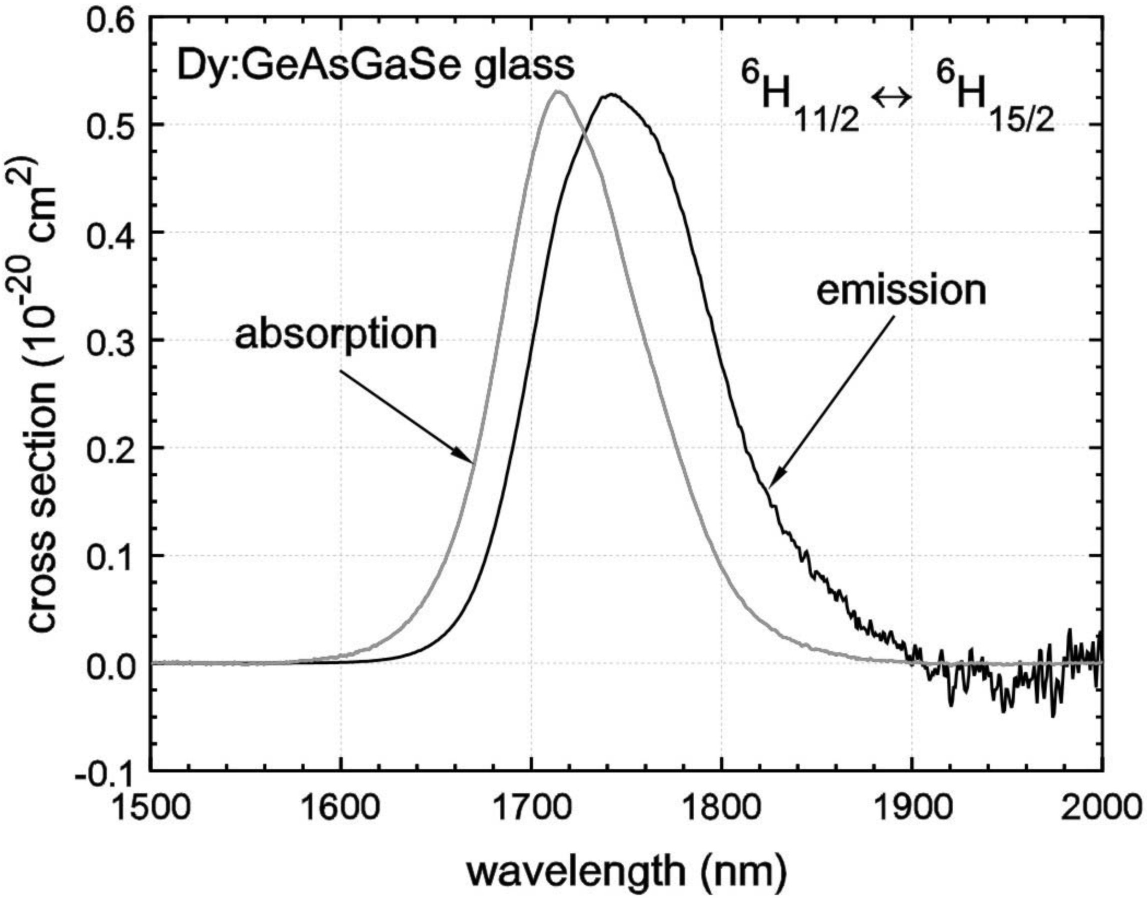
Symbol	Quantity	Value
N	Dy ion density	7×10^{19} cm^{-3}
a	core radius	5.5 μm
NA	numerical aperture	0.2
R_{CL}	inner cladding radius	30 μm
α_2	fiber loss at 3 μm	1 dB/m
τ_3	lifetime of level 3	2 ms
τ_2	lifetime of level 2	5.2 ms
β_{32}	branching ratio for 3→2 transition	0.15
$R_{1,out}$	output coupler reflectivity for λ_1	0.05
$R_{1,HR}$	high reflector reflectivity for λ_1	1
$R_{2,out}$	output coupler reflectivity for λ_2	0.9
$R_{2,HR}$	high reflector reflectivity for λ_2	1
σ_{32}	peak cross section at 4383 nm	1.59×10^{-20} cm^2
σ_{21}	peak cross section at 2926 nm	1.14×10^{-20} cm^2
σ_p	absorption cross section at 1710 nm	0.52×10^{-20} cm^2



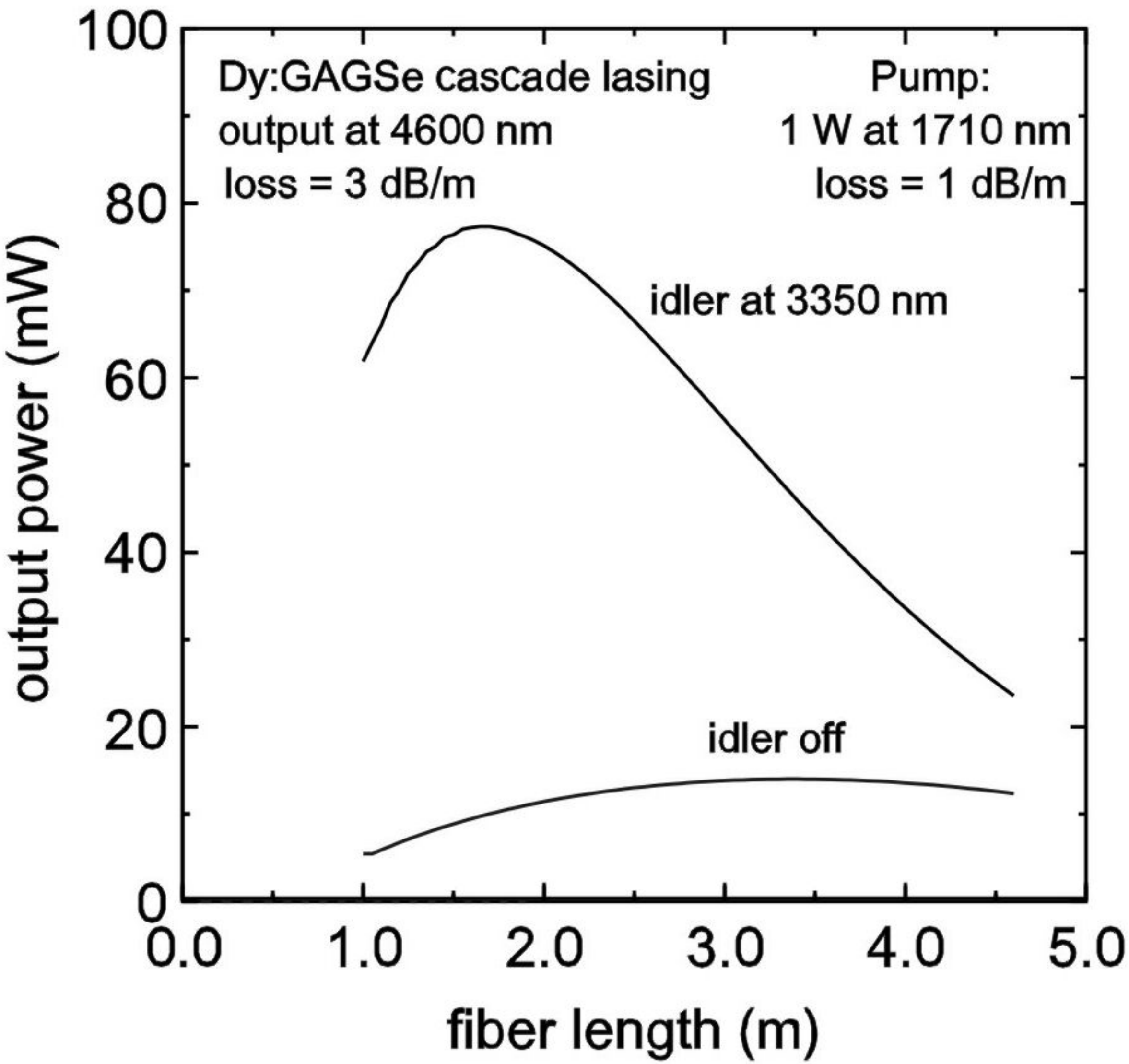
- emission measured from fluorescence
- absolute cross sections scaled to agree with oscillator strength (obtained from Judd-Ofelt analysis)
- absorption spectrum calculated from emission spectrum using reciprocity (McCumber) relation



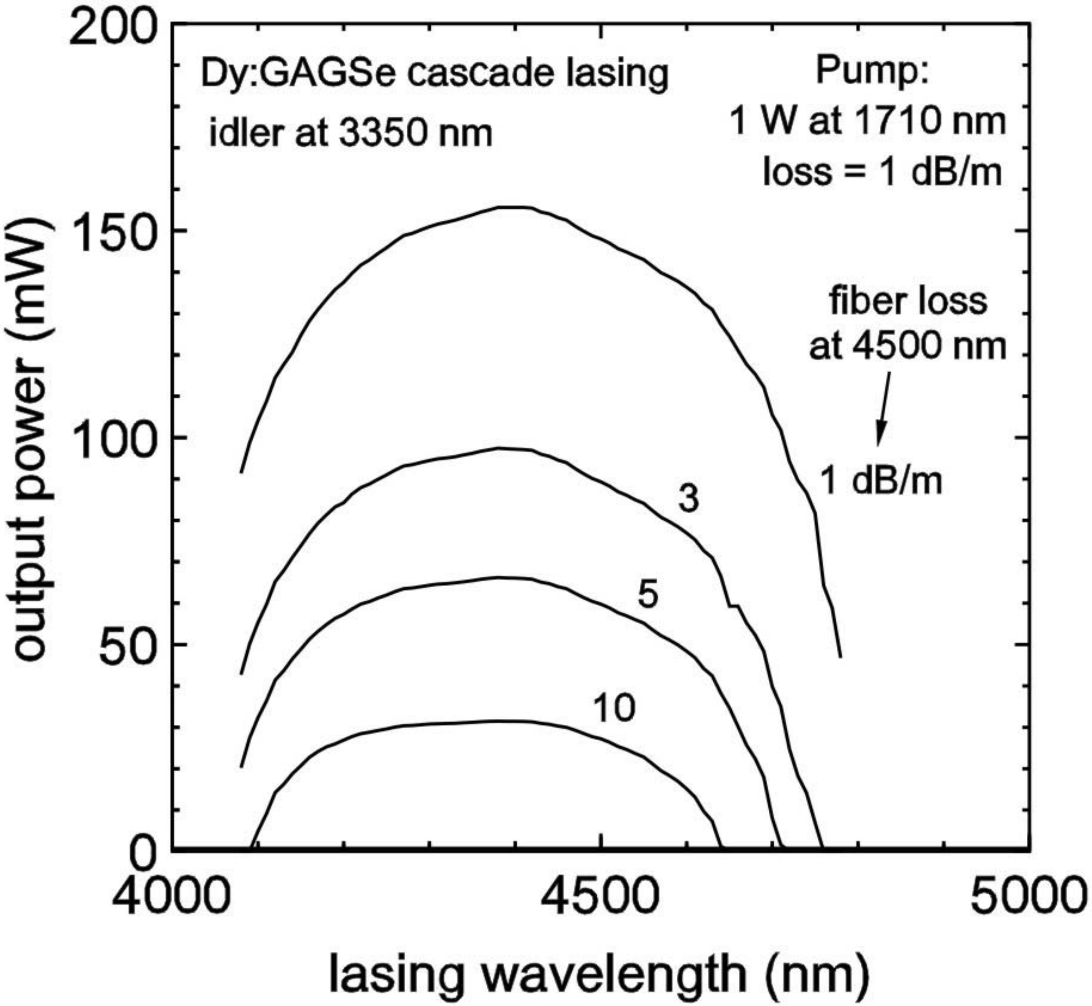
- Optimum idler wavelength is on long-wavelength side of $^6H_{13/2} \rightarrow\ ^6H_{15/2}$ transition (3350 nm)
- This is where $\sigma_{ems} >> \sigma_{abs}$, and level 2 is depleted most efficiently



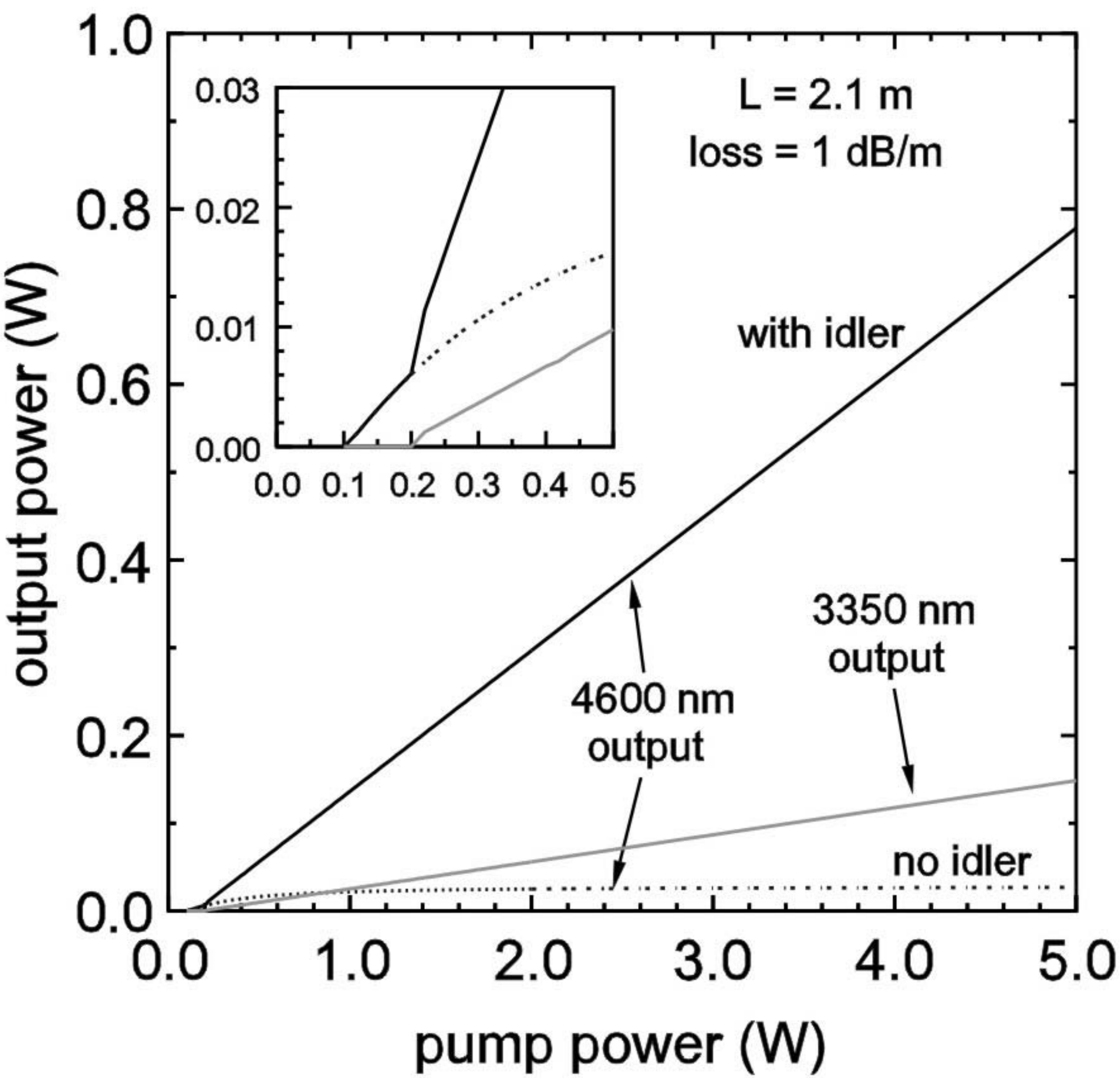
Optimum pump wavelength is 1710 nm



The idler recycles the excited-state population faster, resulting in increased gain on the 4600 nm transition, and shorter optimum fiber lengths



Efficient lasing from 4200-4600 can be obtained if the fiber loss is kept below 3 dB/m



Increase in output power at 4600 nm with simultaneous lasing of idler at 3350 nm is especially large for higher pump power

Summary of Dy fiber laser modeling

- cascade lasing scheme will result in a highly efficient and power-scaleable laser around 4600 nm

- Significant enhancements in efficiency are predicted compared with a traditional single-laser-wavelength scheme

- A key requirement for efficient operation will be fiber losses in the 1-3 dB/m range or smaller.

- high loss in the 4.5 μm region due to HSe impurities may be reduced by special purification techniques [B. Cole et al., *J. Non-Cryst. Solids*, vol. 256&257, pp. 253-259, 1999], and losses in the few dB/m range should be feasible

Conclusions

- Fiber lasers can be designed for efficient operation in the $4 < \lambda < 8$ μm range using rare earth doped chalcogenide glass
- In predicting device performance, caution needed when using multiphonon energy-gap law
- Watt-class fiber lasers at ~3 μm have been demonstrated using fluoride glass, but no experimental reports yet of rare earth doped chalcogenide glass fiber lasers
- Modeling of a Dy doped selenide fiber laser at 4.6 μm shows that cascade lasing improves efficiency by preventing bottle-necking in lower laser level
- Fiber attenuation above ~1 dB/m leads to significantly reduced output power. Need to limit H-Se content of glass.